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THESIS

ON THE QUESTION OF ACCUMULATION
OF ICE-MELT WATER SOUTH OF THE ICE IN THE
CHUKCHI SEA

by

Robert Glenn Handlers

March 1977

Thesis Advisors:

R.G. Paquette
R.H. Bourke

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A report submitted to
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On the Question of Accumulation
of Ice-Melt Water South of the Ice in the
Chukchi Sea

by

Robert Glenn Handlers
Lieutenant, United States Navy
B.S., The Pennsylvania State University, 1969

Submitted in partial fulfillment of the
requirements for the degree of

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from the

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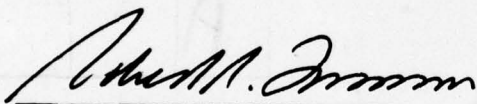
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ABSTRACT

The processes controlling the distribution of melt water from the retreating ice edge in summer in the Chukchi Sea were examined in order to provide evidence of the flow regime. Current and salinity data from the National Oceanographic Data Center (NODC) files and from four MIZPAC cruises were utilized in this work. An increase in melt-water content towards the ice in the approximately 30 km wide ice-melt zone as well as an abrupt salinity decrease were observed. This effect was presumed to be due to scattering of ice from a diffuse ice margin accompanied by melting. North of the ice edge the fresh-water content was greater than that of southerly water by an amount $(150-200 \text{ gm/cm}^2)$ equivalent to the thickness of the ice cover. These findings together with an independent comparison of transport times and ice satellite data produce good evidence that the current flows faster than the ice retreats during summer in the eastern half of the Chukchi Sea.

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I. INTRODUCTION

During the course of investigation in the marginal sea-ice zone as a part of the MIZPAC¹ program, interest has been generated in the processes controlling the distribution of melt water from the retreating ice edge in summer in the Chukchi Sea. This thesis investigates the possibility that the distribution of ice-melt can provide evidence of the flow regime in the Chukchi Sea. Paquette and Bourke (1976), working with MIZPAC 1974 data, found a zone of dilute water south of the ice and hypothesized that this dilute water could be the signature of ice-melt water which was being carried northward more slowly than the ice was retreating. This study brings to bear appropriate historical data in an effort to determine the general validity of this hypothesis. In the end it will be shown that the mean current flows northward faster than the ice retreats, which implies that the greater part of the ice-melt water is pushed northward under the ice. Over considerable portions of the ice margin, the dilute water is confined to a narrow band close to the ice. However, in the 1974 and 1975 MIZPAC data, there were sizable boluses of fresh water well to the south of the ice

¹MIZPAC refers to Marginal Sea-Ice Zone Pacific, an investigation of the Pacific Marginal Sea-Ice Zone under the general direction of the Arctic Submarine Laboratory, Naval Undersea Center, San Diego.

which is explained as a phenomenon localized in time and space.

To test the hypothesis of the existence of an ice-melt zone, the following analyses were undertaken. Initially, a number of vertical salinity profiles were examined for evidence of a more-or-less sharp transition in the near-surface waters from high to low salinity south of the ice. Figure 1 consists of three salinity profiles taken from MIZPAC 1974 data along a south-north section approaching the ice. It can be seen that the isohaline water at Station 22, approximately 100 km from the ice, is water from the southern Chukchi Sea which has experienced no dilution by ice-melt water. The low salinity values of Station 24, located within about 10 km of the ice edge, clearly shows the dilution caused by the melting ice. Station 23, approximately 45 km outside the ice, shows that marked dilution of near-surface waters can occur at distances remote from the retreating ice edge. Several examples of sections taken from the MIZPAC data showed this marked near-surface salinity reduction, but few profiles encompassed a sufficient number of stations which showed the progressive dilution from well outside the ice to within the ice. Therefore, further evidence was sought.

Next, all the summer Chukchi Sea data in the National Oceanographic Data Center (NODC) files up to 1972 and the data from four MIZPAC cruises were examined for additional

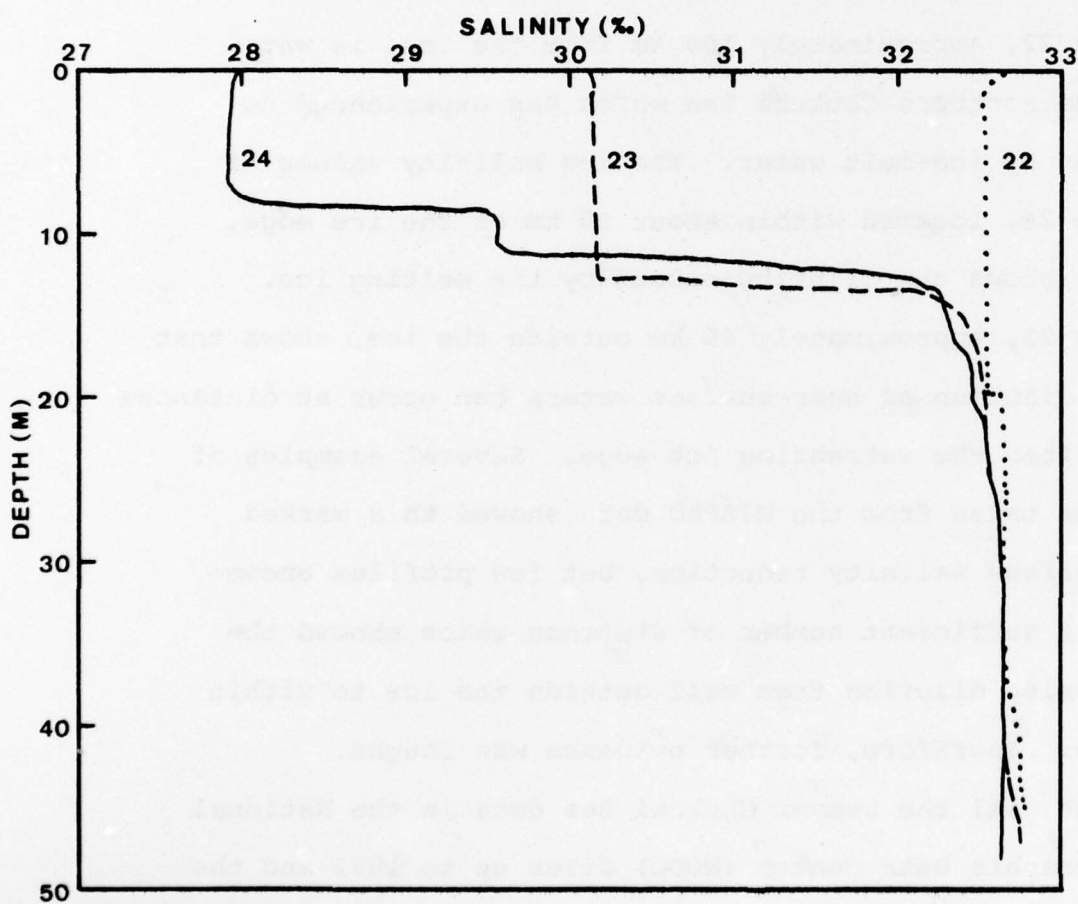


FIGURE 1. Vertical salinity sections from MIZPAC 1974, stations 22, 23, and 24.

evidence of salinity dilution by ice melt. Surface salinity and five-meter-depth salinities were classified into four salinity groups and plotted by months. These results indicated low-salinity water in the vicinity of the ice and on the eastern side of the Chukchi Sea. The low salinities near the coast and in Kotzebue Sound raised the suspicion that the salinity change near the ice was not entirely due to ice melt, i.e., some low-salinity water may have had its origin in Bering Strait or in the Kobuk River. It was also considered possible that some ice-melt water had been mixed downward and was not being found in the plots of the near-surface salinities.

To examine the latter possibility, the fresh water content within a water column was obtained by integration for all MIZPAC stations and the results plotted. These plots showed that a rapid increase in fresh water content occurred near the ice edge and beyond it, and that the dilution could be ascribed to melting from an appropriate thickness of ice.

An attempt was made to compare the observed rate of ice retreat from satellite data with the northward rate of flow using historical water velocity data and computed transport rates. This analysis provided an independent verification of the conclusion inferred from the previous analyses that the near-surface waters indeed flow northward faster than the ice retreats.

II. GENERAL OCEANOGRAPHY

An understanding of the role of ice-melt water in the Chukchi Sea depends upon several factors, and upon the answers to the following basic questions: Does northward-flowing water travel as fast as the ice retreats? How can one describe background water properties so that the presence of ice melt may be seen as a deviation from the background? Are there sources of fresh water other than ice melt, which may also contribute to the deviation? To answer these questions it is necessary to review a limited amount of the general oceanography, and in particular that which concerns the northward flow of the waters from Bering Strait, whose properties vary with position in the Strait and with time. Previous studies (Paquette and Bourke, 1976; Zuberbuhler and Roeder, 1976) have suggested that the rate of ice melt is influenced by the speed and heat content of the northward-flowing water. Seasonal differences, therefore, affect the rate at which melt water is provided. Another seasonally influenced parameter is the position of the ice edge which is also important to the problem. Unfortunately, most of the historical data do not give the position of the ice edge and it must be inferred indirectly.

The following section will rely heavily on the work of Coachman, Aagaard and Tripp (1976), who will henceforth be designated as CAT. The Chukchi Sea is a shallow

continental-shelf sea with an average depth of about 45 m. Ice normally covers the Chukchi Sea from November to June, and then melts back fairly rapidly in an irregular fashion to a northern limit of about 73° N latitude, achieved in mid-September. Bering Strait is a narrow, shallow (30-50 m) passage between Alaska and Siberia which connects the Bering and Chukchi Seas. The dominant feature of the Bering Strait, as demonstrated by CAT, is the general northward direction of the mean flow, at least during the summer.

The following specific flow and water property characteristics through Bering Strait are presented here as they are necessary for the transport calculations used later in this study. In the eastern part of Bering Strait CAT found in mid-summer (August) a sharp pycnocline at 10-15 m. which typically separates a surface layer of warm (9-10°C), fairly low-salinity (30-31‰) water from a deeper, colder (1-4°C), more saline (31-32.7‰) water. The western part contains relatively uniform cold (1-4°C) and saline (32.7-33‰) water. Earlier in the summer less dilution in the eastern part of Bering Strait is observed. Concurrent with the arrival of Yukon River water in the eastern Bering Strait in August, salinities decrease to approximately 29‰. Higher salinities return during the month of October. CAT also report that strong velocity shears occur between these water masses, e.g., the flow in the upper layer in the eastern part of the Strait commonly exceeds 100 cm/sec

while the deeper-lying water has intermediate speeds of 30-60 cm/sec. The flow through the western channel is slower and more uniform.

CAT identify three water masses in Bering Strait, arranged laterally from east to west, and differentiable on the basis of salinity: Alaskan Coastal, Bering Shelf, and Anadyr Waters. Within a short distance north of Bering Strait, the Anadyr and Bering Shelf Waters are combined to form Bering Sea Water. Bering Sea Water dominates the central and western part of the southern Chukchi Sea and has a median salinity of 32.5 ‰. The Alaskan Coastal Water, according to CAT, lies to the east of the Bering Sea Water and is joined by effluent from Kotzebue Sound. They state that there is no way to distinguish between Alaskan Coastal and Kotzebue Sound Waters because of similar temperature and salinity characteristics. CAT indicate the temperature and salinity properties of the Alaskan Coastal Water are variable, but in general, the salinities range between 30.5 ‰ and 32.0 ‰.

The general current pattern through Bering Strait and in the southern portion of the Chukchi Sea in mid-summer can be inferred from individual current measurements taken during the STATEN ISLAND 1968 and OSHORO MARU 1972 cruises (Figures 2 and 3). These measurements demonstrate the general northward direction of flow and the variability of the currents with depth. A schematic of the surface flow pattern for the Chukchi Sea, as constructed by CAT from



FIGURE 2. STATEN ISLAND current measurements, July, 1968
(from Coachman, et al., 1976).

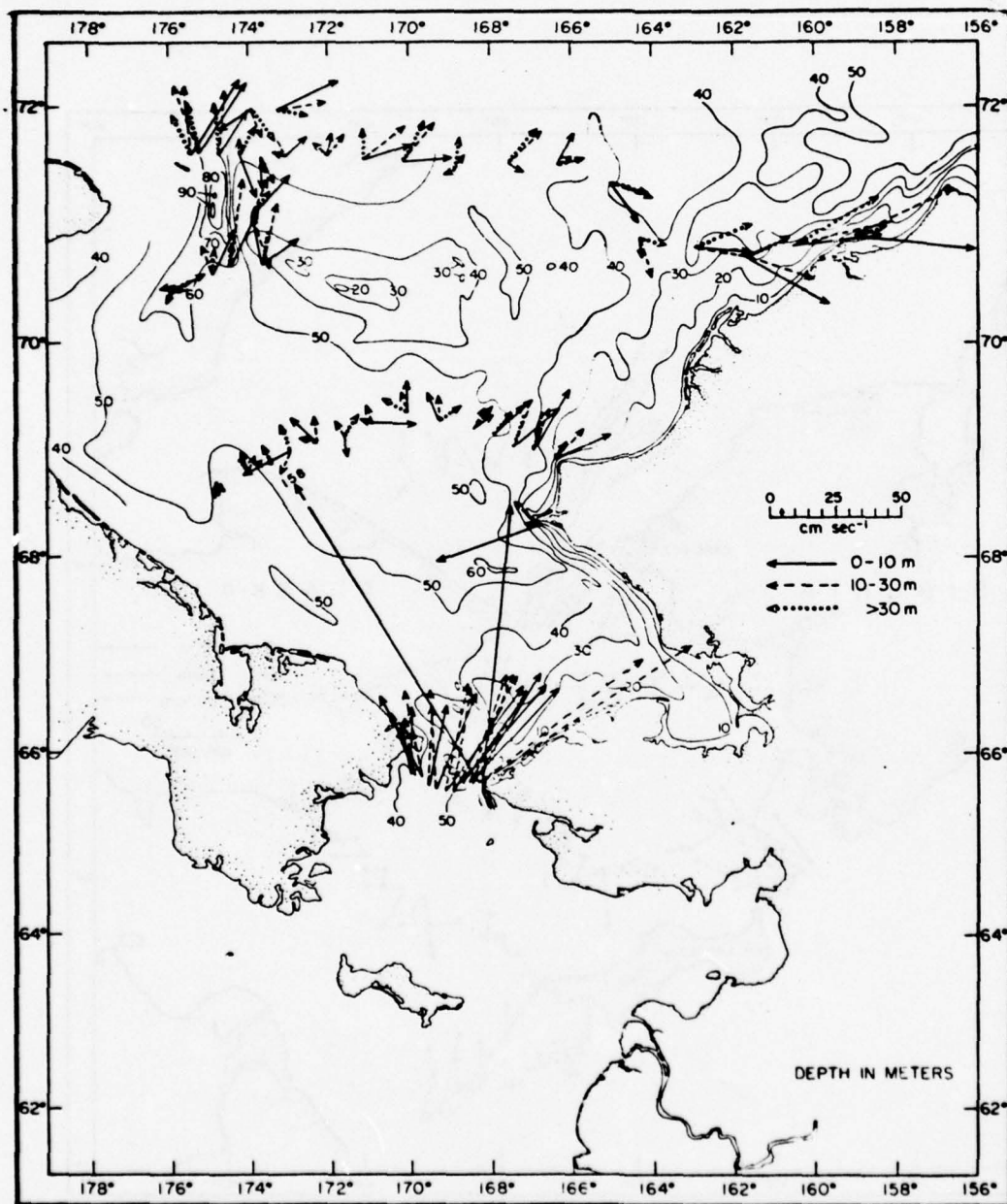


FIGURE 3. OSHORO MARU current measurements, July, 1972
(adapted from Coachman, et al., 1976).

historical current measurements (Figure 4), indicates that the current flows more rapidly on the eastern side of the Chukchi Sea with an initial speed of 150 cm/sec. As the water proceeds northward, the average speed decreases to 20-30 cm/sec, while over the south-central Chukchi Sea, the average speed is 15-25 cm/sec.

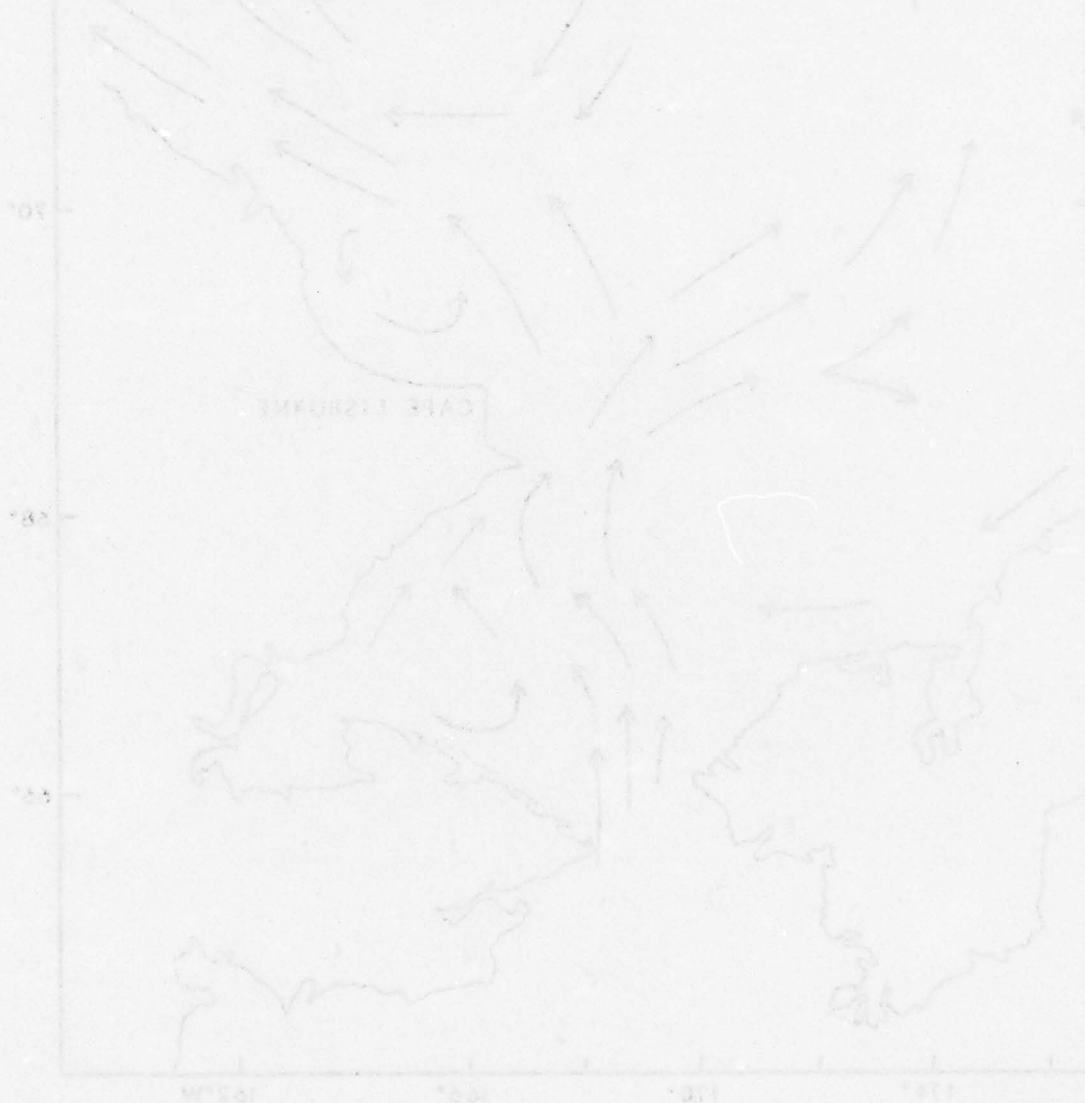


FIGURE 4. Upper level flow patterns (adapted from
Cochran, et al., 1976)

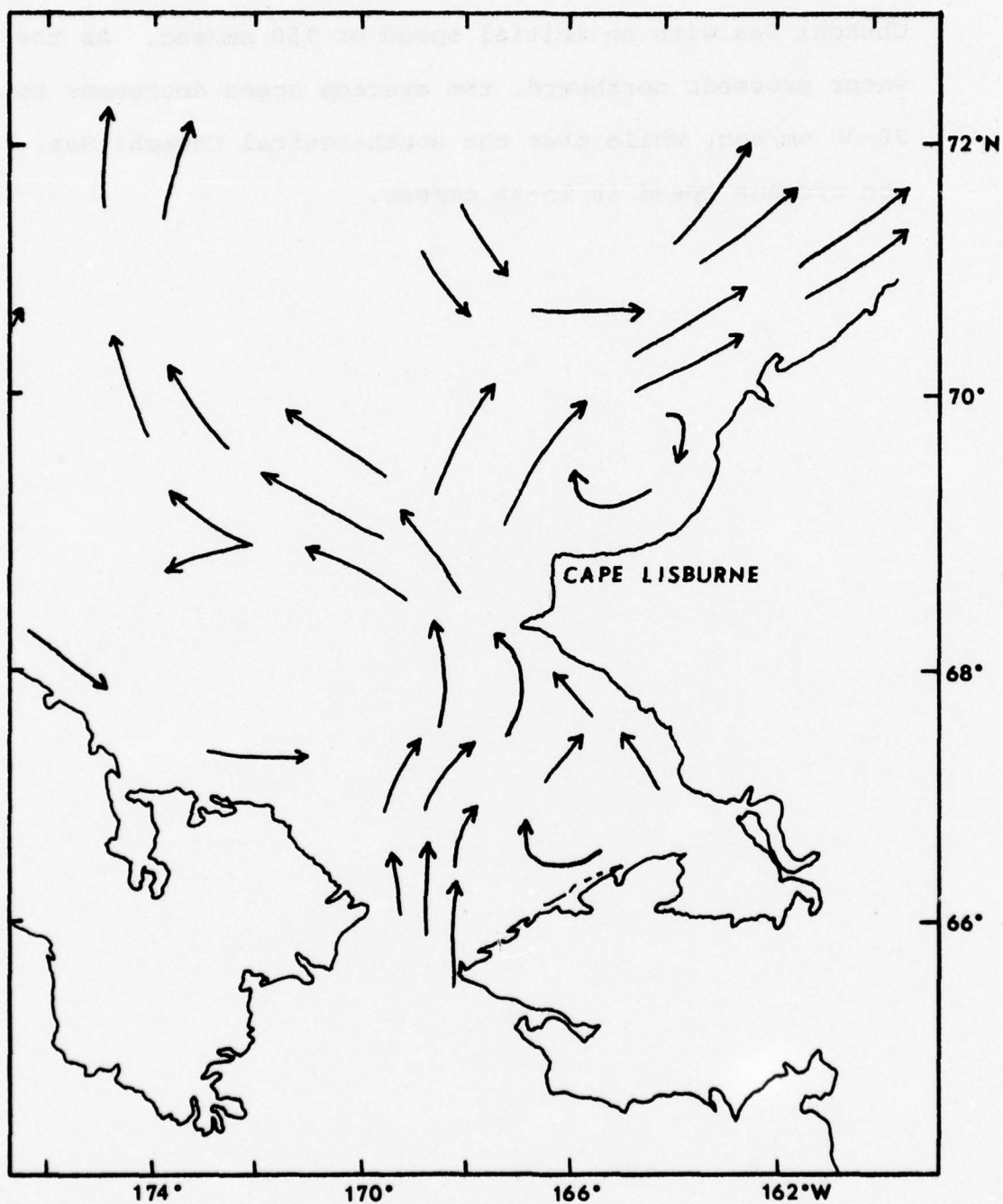


FIGURE 4. Upper level flow patterns (adapted from Coachman, et al., 1976).

III. METHODS

All of the summer data in the Chukchi Sea from 1922 to 1972 on file at NODC and the MIZPAC 1971, 1972, 1974 and 1975 data were examined to find evidence of the general presence of dilute water south of the ice. Computer programs were used to retrieve stored data from magnetic tapes and to create monthly plots of MIZPAC and NODC surface and five-meter-depth salinities. Originally, an attempt was made to contour salinities on the NODC plots, but the results were too noisy. However, when the salinities were grouped into ranges and plotted as coded symbols, the noise was eliminated to a great extent.

NODC data were combined by months (July-September) regardless of year while salinity plots were created for each of the MIZPAC cruises. In an attempt to further reduce the noise in the NODC surface salinity plots, it was assumed that the noise might be due to year-to-year variability in the position of the ice edge. Accordingly, the monthly plots were separated into severe and not-so-severe years using Barnett's severity index (1976). This severity covers the time period from 1955 to 1972; hence, monthly plots were only presented for this time period. There was only a slight improvement in consistency as a result of this breakdown; therefore, the data were recombined and analyzed.

As the surface and five-meter-depth salinity plots showed essentially the same information, only the surface plots were used for analysis.

The integrated fresh-water content was then computed for the MIZPAC data by numerically integrating the following equation: $W_z = \rho \int_0^z \frac{SR-S}{SR} dz$. This calculation yields the weight in grams of fresh water in a water column of 1 cm^2 area and height z , measured to the surface, as compared to a similar column of water with a reference salinity (SR) of 33.33‰ . The latter choice is a rough median value for the higher salinities found near the bottom south of the ice. The density of the water (ρ) is equal to 1.03 gm/cm^3 and S represents the average salinity in the depth increment, dz . These fresh-water contours were based on a reference depth of 30 m, a compromise so as not to exclude too many shallow-water stations, but not to exclude too much fresh water from the near-bottom layers.

The fresh-water content of a water column suffers one serious difficulty as a diagnostic tool: it is not necessarily a conservative parameter, even in the absence of mixing. If an upper, fresh-water-rich layer converges or diverges to a greater extent than a lower layer, a change in fresh water content will result. For example, if a dilute water column of 30 m depth were concentrated into an upper layer of 10 m, the fresh-water content would decrease. It will be shown that the assumption of negligible

convergence or divergence is true in the vicinity of the ice edge, but is not necessarily tenable south of the ice.

In an attempt to predict both the time-varying water properties north of Bering Strait and the velocity of the water at the ice, the water speeds and time of transport were computed for the waters issuing from four vertical slices through Bering Strait. These four streams (designated I, II, III, and IV from east to west) were selected to correspond roughly to the direction of the upper-level flow pattern (CAT, 1976). Transport values through Bering Strait were calculated for each stream using STATEN ISLAND 1968 current measurements and the cross-sectional areas of each stream. The resulting transports for streams I-IV were 0.630 Sv, 0.270 Sv, 0.340 Sv and 0.390 Sv, respectively, yielding a total transport through Bering Strait of 1.63 Sv which is in close agreement with Coachman and Aagaard's (1974) value of 1.5 Sv.

Streams I, II, and III were then separated into trapezoidal segments, as shown in Figure 5. Transport times within these streams, north to 70° latitude, were calculated using trapezoidal integration (Figure 6). Velocities in the vertical were assumed uniform from top to bottom. Transport times rather than actual current speeds were used to monitor the flow rate in the southern Chukchi Sea as current data in this region are extremely sparse. Calculations were discontinued at 70° latitude because the flow

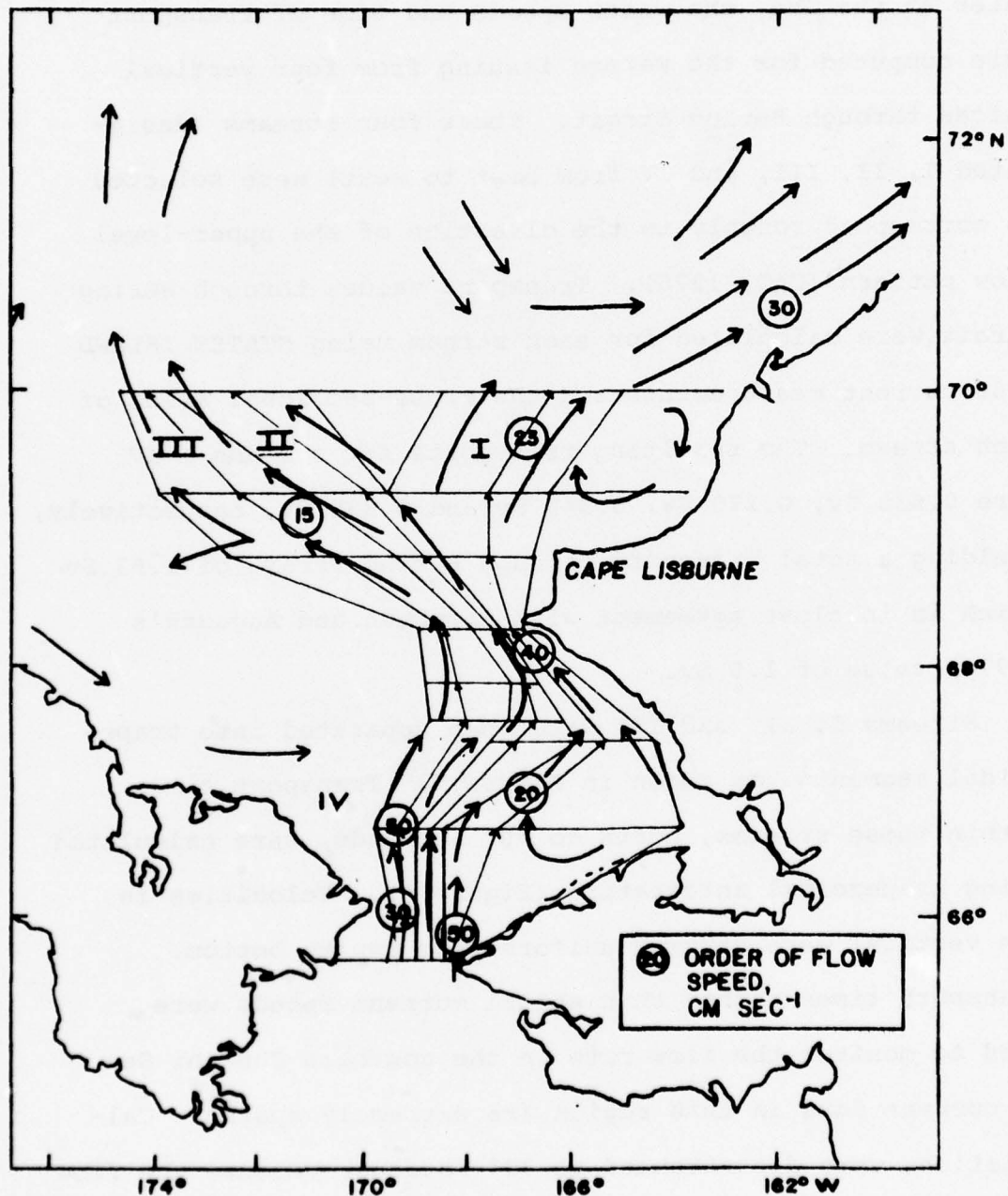


FIGURE 5. Transport streams in the southern Chukchi Sea based on the assumed upper-level flow pattern of Coachman, et al. (1976).

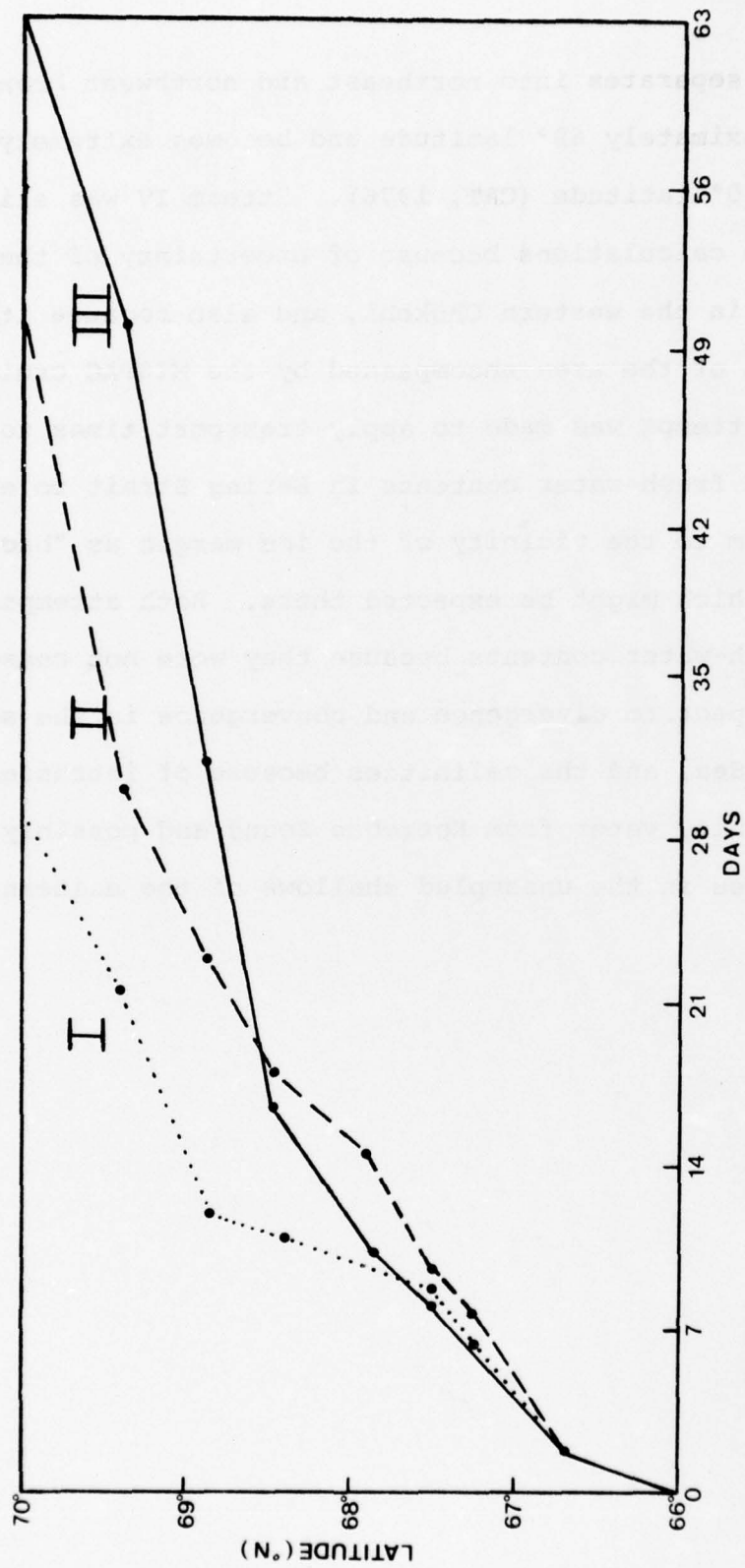


FIGURE 6. Time of transport for streams I, II, and III from Bering Strait northward to 70°N latitude.

pattern separates into northeast and northwest branches at approximately 69° latitude and becomes extremely variable beyond 70° latitude (CAT, 1976). Stream IV was eliminated from the calculations because of uncertainty of the flow pattern in the western Chukchi, and also because it was to the west of the area encompassed by the MIZPAC cruises.

An attempt was made to apply transport times to salinities and fresh-water contents in Bering Strait to extrapolate them to the vicinity of the ice margin as "background" values which might be expected there. Both attempts failed, the fresh-water contents because they were not conservative with respect to divergence and convergence in the southern Chukchi Sea, and the salinities because of intrusion of low-salinity water from Kotzebue Sound and possibly low salinities in the unsampled shallows of the eastern Bering Strait.

IV. RESULTS

Vertical salinity profiles from the MIZPAC cruises indicated that marked dilution of the near-surface waters occurred well outside the ice margin with increasing dilution observed as the water approached the ice edge (Figure 1 in Section 1). The position of the initial dilution, which was assumed by Paquette and Bourke (1976) from MIZPAC 1974 data to be the initial signature of ice-melt water, occurred from 50 to 100 km outside the ice edge. The ice-melt signature appears to be a widespread phenomenon south of the ice and its position appears to vary with the location of the ice edge in the Chukchi Sea, i.e., the ice-melt signature shifts progressively northward with the retreat of the ice. The distance of the ice-melt signature from the ice edge is variable in time and space because the ice retreats in an irregular pattern across the Chukchi Sea and its rate of retreat varies from year to year. Dilution from ice melt can occur at distances as great as 100 km from the ice due to fluctuations in the position of the ice margin in response to wind shifts (time scale of a few days) and to melting of stray ice floes or isolated patches of ice.

The monthly surface salinity plots from the combined NODC data also showed that the low salinities in summer were concentrated in the northern portion of the Chukchi Sea.

Only the results from the August data are discussed as the results from July and September are similar. Salinities less than 30 ‰, shown in Figure 7 as ●'s and x's, are found clustered in a narrow band at a latitude where the ice edge might be expected to be found in August. The few moderately high salinities in this region (■'s) were probably taken at stations fairly remote from the ice edge. (Ice concentration data are not present in the NODC data.) To the south of this band of dilute water, Figure 7 shows no evidence of dilution by ice-melt within the central Chukchi Sea. Near-surface salinities are generally everywhere greater than 31.5 ‰ (◆'s) which is undiluted Bering Sea Water as identified by CAT (1976). The zone of moderate salinity water north of Cape Lisburne is Alaskan Coastal Water. The NODC data show that another low-salinity zone is present during the summer in the vicinity of Kotzebue Sound. This is from the discharge of the Kobuk River which peaks in August (USGS, 1973).

The MIZPAC salinity plots are able to confirm the results suggested by the NODC monthly plots in two important ways. Because the location of the ice edge is a known feature of the MIZPAC cruises, it is possible to accurately assess the distribution of ice-melt water found outside the ice margin. Also the MIZPAC cruises penetrated well into the ice, usually 10 n mi but occasionally as far as 30 n mi behind the ice front, providing information on the amount of dilution occurring under the ice.

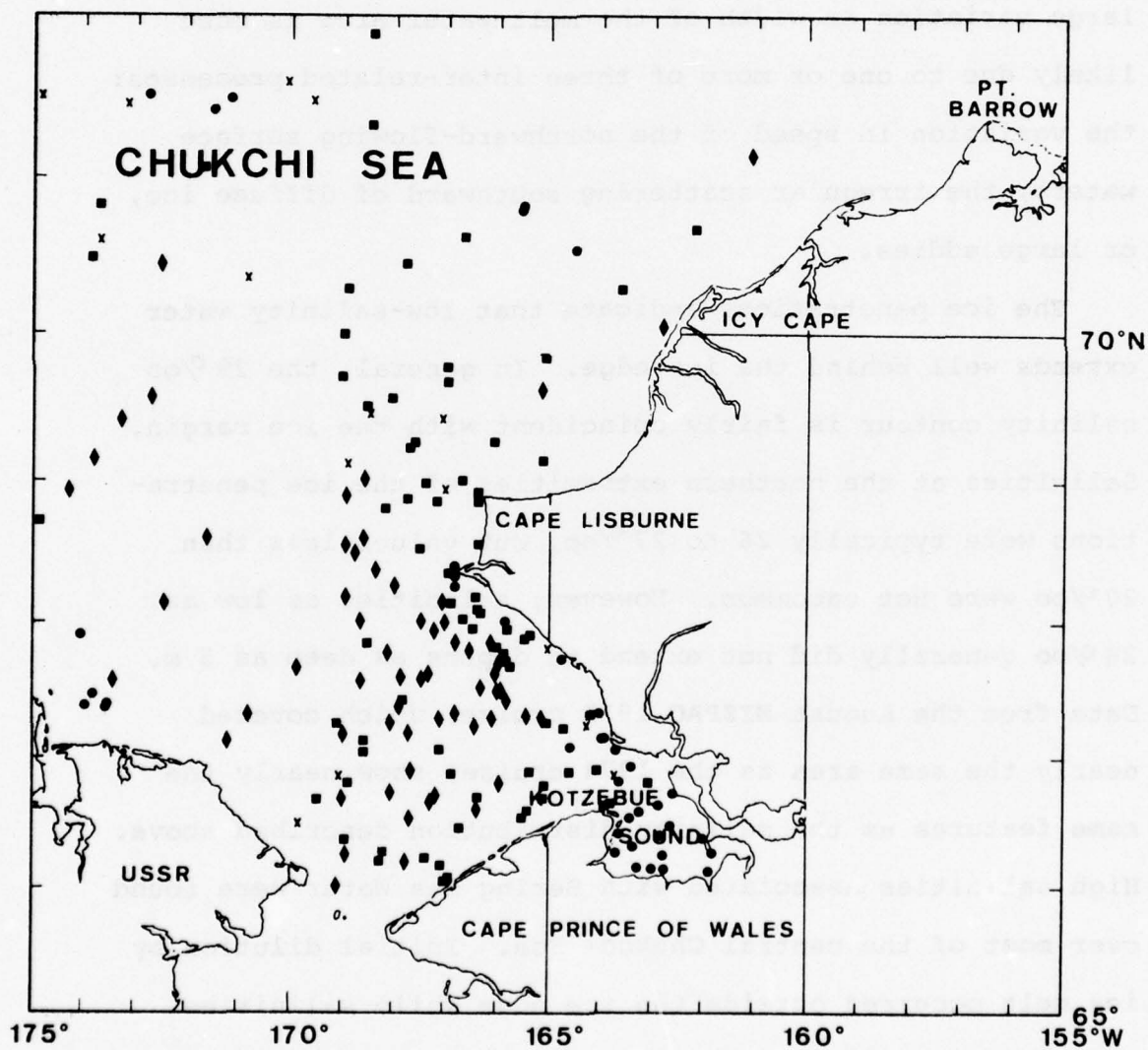


FIGURE 7. Monthly plot of codified surface salinities for August. Salinities less than 29 ‰ - circle, 29-30 ‰ - x, 30-31.5 ‰ - square, greater than 31.5 ‰ - diamond.

The MIZPAC 1974 cruise data, taken during the last half of July, show that undiluted Bering Sea Water covers most of the central Chukchi Sea south of Point Hope (Figure 8). Initial dilution by ice melt occurs as far as 50 km outside the ice edge in the central Chukchi, but occurs less than 10 km from the ice northwest of Icy Cape. This large variation in width of the melt-water area is most likely due to one or more of three inter-related processes: the variation in speed of the northward-flowing surface waters, the irregular scattering southward of diffuse ice, or large eddies.

The ice penetrations indicate that low-salinity water extends well behind the ice edge. In general, the 29 ‰ salinity contour is fairly coincident with the ice margin. Salinities at the northern extremities of the ice penetrations were typically 26 to 27 ‰, but values less than 20 ‰ were not uncommon. However, salinities as low as 20 ‰ generally did not extend to depths as deep as 5 m. Data from the August MIZPAC 1975 cruise, which covered nearly the same area as the 1974 cruise, show nearly the same features as the salinity distribution described above. High salinities associated with Bering Sea Water were found over most of the central Chukchi Sea. Initial dilution by ice melt occurred outside the ice edge while salinities rapidly decreased from the ice edge northward to the limits of ice penetration. The 1975 data did show an exception to

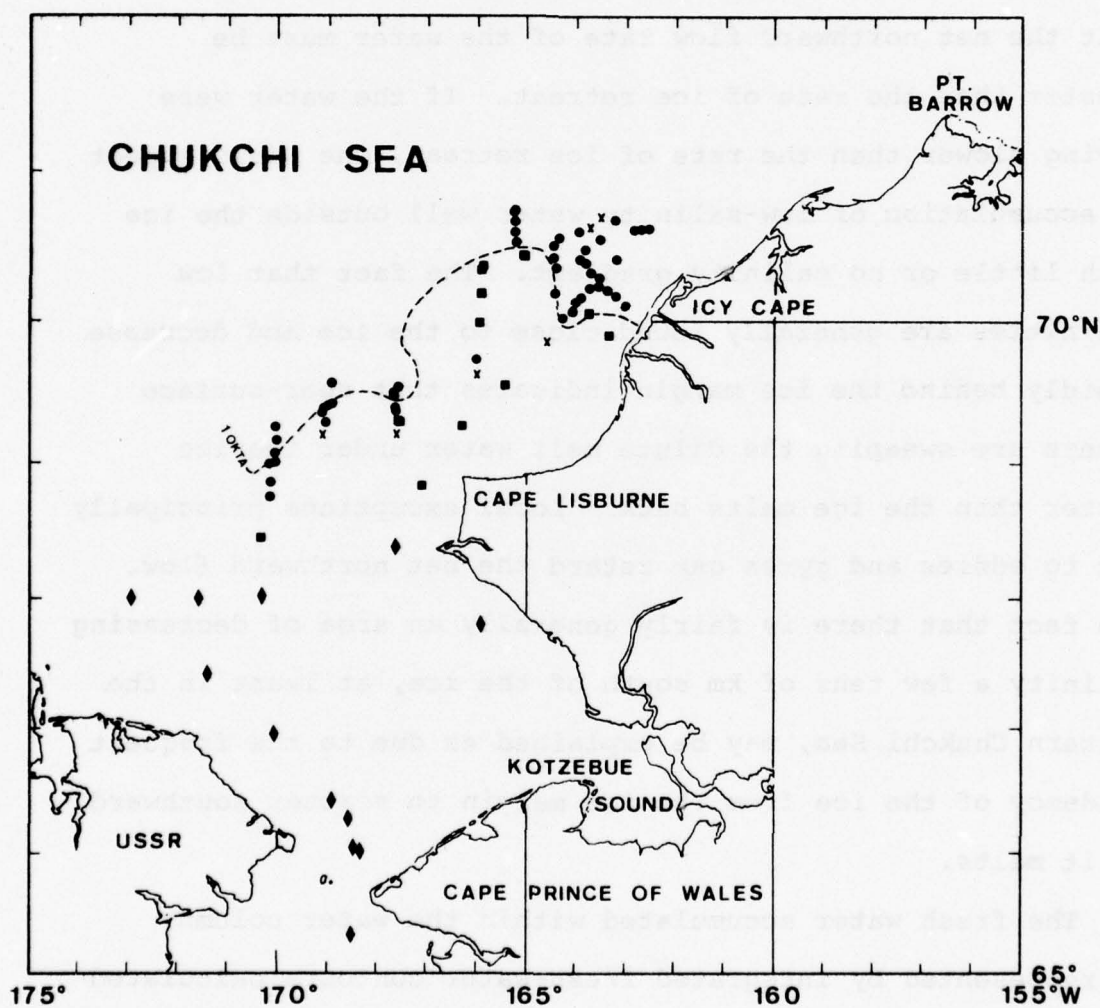


FIGURE 8. MIZPAC 1974 symbolic plot of salinities. The dashed line represents the 1 OKTA ice edge. Salinities less than 29 ‰ - circle, 29-30 ‰ - x, 30-31.5 ‰ - square, greater than 31.5 ‰ - diamond.

this pattern in the bight north of Cape Lisburne where the 29 ‰ contour extended well south of the ice edge (Figure 9). It is possible that diluted melt water was trapped in the gyre north of Cape Lisburne observed during this cruise (Zuberbuhler and Roeder, 1976) and previously reported in this area by CAT (1976).

This salinity distribution leads one to the conclusion that the net northward flow rate of the water must be greater than the rate of ice retreat. If the water were moving slower than the rate of ice retreat, one would expect an accumulation of low-salinity water well outside the ice with little or no salinity gradient. The fact that low salinities are generally found close to the ice and decrease rapidly behind the ice margin indicates that near-surface waters are sweeping the dilute melt water under the ice faster than the ice melts back. Local exceptions principally due to eddies and gyres can retard the net northward flow. The fact that there is fairly generally an area of decreasing salinity a few tens of km south of the ice, at least in the eastern Chukchi Sea, may be explained as due to the frequent tendency of the ice from the ice margin to scatter southward as it melts.

The fresh water accumulated within the water column, as represented by integrated fresh-water contours calculated from the MIZPAC data, generally showed a marked increase in the immediate vicinity of the ice edge. In interpreting

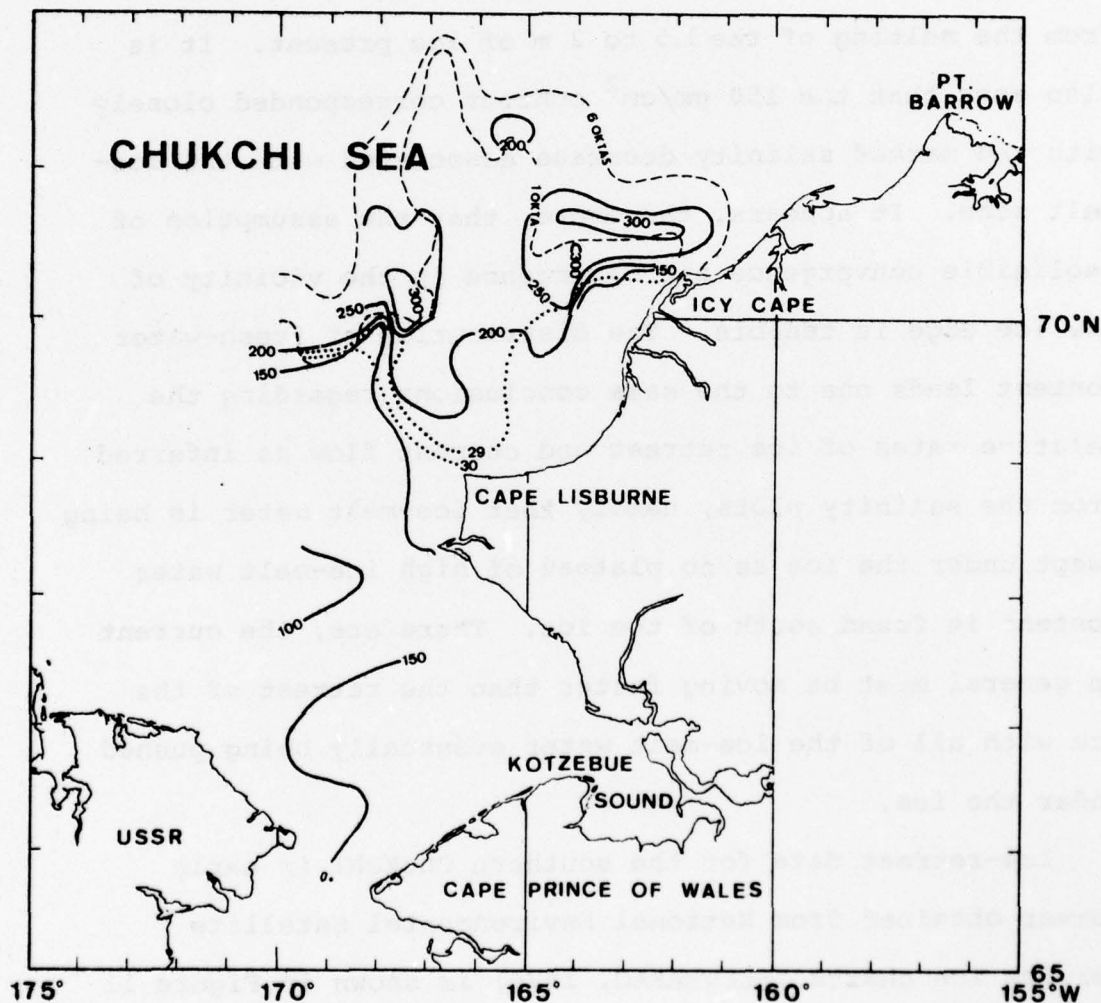


FIGURE 9. MIZPAC 1975 integrated fresh-water content. The dotted lines represent the 29 and 30 ‰ salinity contours. The dashed lines indicate the ice boundaries in OKTAs. Contours of integrated fresh-water content in gm/cm² are shown in solid lines.

these gradients of accumulated fresh water it was initially assumed that convergence and divergence effects were negligible. Figures 9 and 10, based on the MIZPAC 1975 and 1974 data, generally show an increase in fresh-water content from 150 gm/cm^2 found 30 to 50 km outside the ice to more than 300 gm/cm^2 behind the ice margin. This 150-200 gm/cm^2 increase is equivalent to what one might expect from the melting of the 1.5 to 2 m of ice present. It is also seen that the 150 gm/cm^2 contour corresponded closely with the marked salinity decrease associated with the ice-melt zone. It appears, therefore, that the assumption of negligible convergence and divergence in the vicinity of the ice edge is tenable. The distribution of fresh-water content leads one to the same conclusions regarding the relative rates of ice retreat and current flow as inferred from the salinity plots, namely that ice-melt water is being swept under the ice as no plateau of high ice-melt water content is found south of the ice. Therefore, the current in general must be moving faster than the retreat of the ice with all of the ice-melt water eventually being pushed under the ice.

Ice-retreat data for the southern Chukchi in early summer obtained from National Environmental Satellite Service ice charts (FLEWEAFAC, 1976) is shown in Figure 11 for the period 1972 to 1975. When compared with mean water transport times calculated from measured transport rates

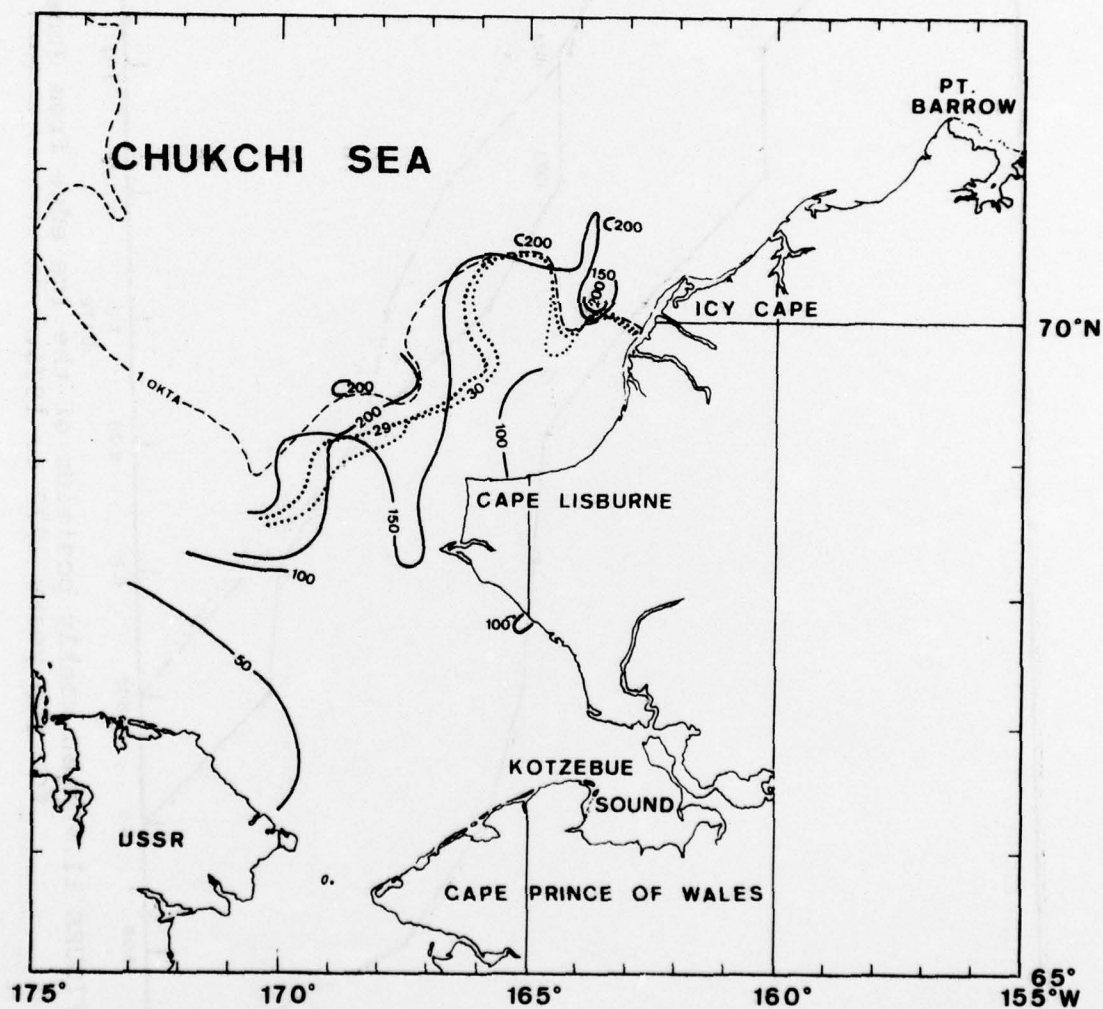


FIGURE 10. MIZPAC 1974 integrated fresh-water content. The dotted lines represent 29 and 30 ‰ salinity contours. The dashed line indicates the 1 OKTA ice edge. Contours in integrated fresh-water content in gm/cm^2 are shown as solid lines.

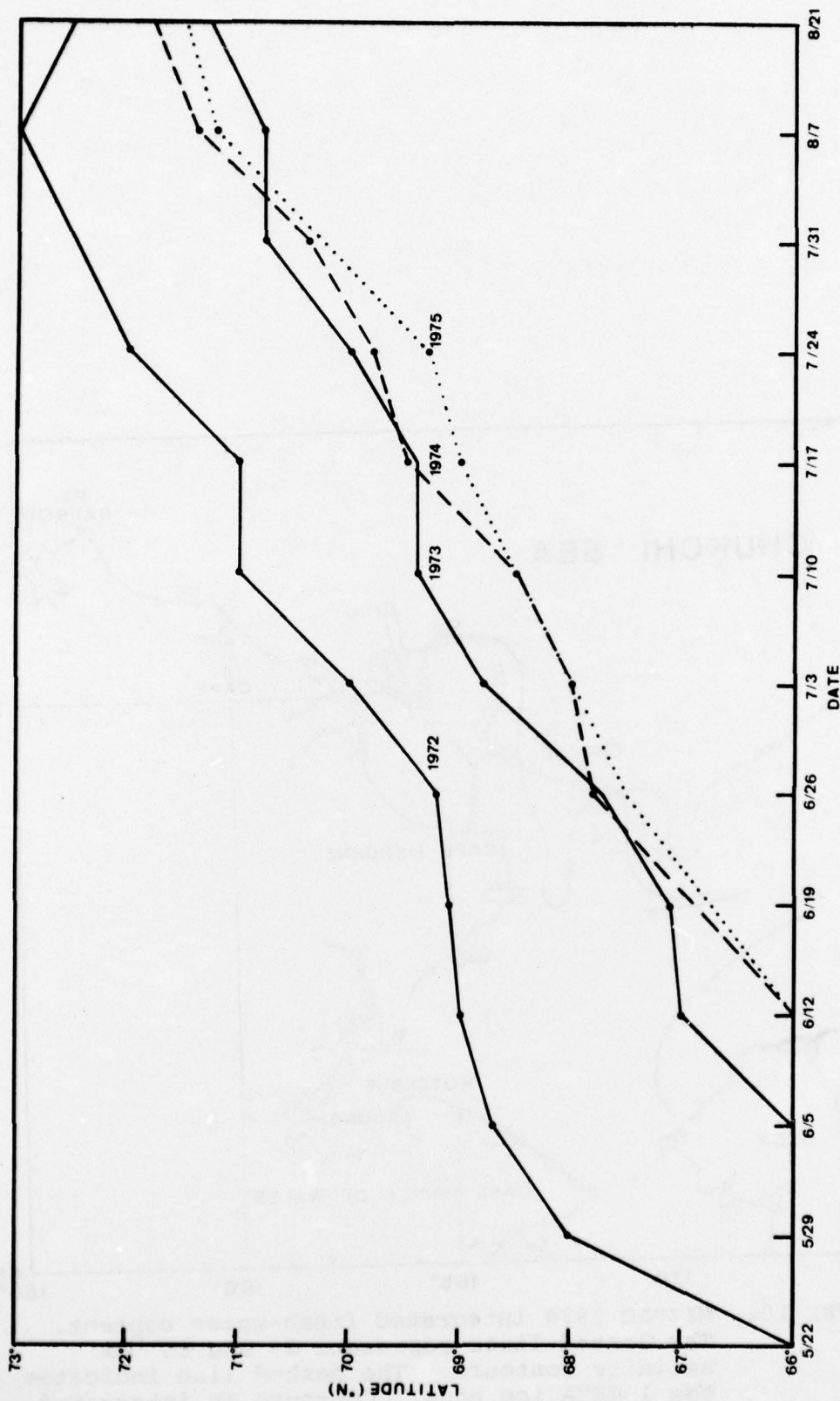


FIGURE 11. Mean weekly position of the ice edge from June to August for the years 1972 to 1975.

through Bering Strait (Figure 6), it is clear that indeed the mean current does flow faster than the mean rate of ice retreat. These calculations indicate that, even in the southern Chukchi Sea, water transport velocities in each stream are greater than the rate at which ice melts back based upon weekly positions of the ice edge. Several exceptions are noted, however, north of 69° latitude. North of this latitude the speed of the current in the central Chukchi (transport streams II and III) was approximately the same as or somewhat slower than the rate of ice retreat. There was also a period of time from late May to early June 1972 when the ice in the central Chukchi Sea retreated more rapidly than the computed velocity. In these cases it could be that the northward flow in the central Chukchi was retarded by gyre-like motion. However, it is likely that the surface current, even in these exceptional cases, was flowing faster than the ice retreated because there is good reason to believe that the upper layer flows more rapidly than the mean of the water column.

Surface current speeds in the Chukchi Sea are expected to be faster than the mean speed because the homogeneous waters in Bering Strait become abruptly layered north of the Strait (NAVOCEANO, 1958), and hence transport velocities in the upper layer must increase if the total transport is to be conserved. This conclusion may be fortified by inspection of the relative velocities in the upper 10 m of water

column as compared to the average of the remainder of the water column. Such a comparison was made for all of the current measurements in the cruises listed in Table I. Here, current magnitudes were regarded as more appropriate than northerly components because of the oscillatory nature of the currents. The results of Table I verify that the upper 10 m of the water column, which contained most of the fresh water, travels faster than the lower half of the water column by 15 to 50 percent. Therefore, the comparison of transport velocity and observed ice retreat rate reinforce the previous conclusion that the northward flow of near-surface water in the Chukchi Sea exceeds the rate at which the ice edge is melted back.

TABLE I. Comparison of the mean current speed of the upper 10 m and the mean speed over the remainder of the water column

<u>Cruise</u>	<u>Location</u>	<u>Top (cm/sec)</u>	<u>Bottom (cm/sec)</u>
OSHO RO MARU 1972	Bering Strait	51.5	43.8
OSHO RO MARU 1972	69° latitude	15.8	10.9
STATEN ISLAND 1968	Bering Strait	59.9	49.0
STATEN ISLAND 1968	67° latitude	35.8	30.8

V. CONCLUSIONS

The following conclusions resulted from this study:

Good evidence was found that the current flows northward faster than the ice retreats in the summer months in the eastern half of Chukchi Sea. An earlier hypothesis of an ice-melt zone moving more slowly than the ice edge retreats was not substantiated.

A band of water approximately 30 km wide exists south of the ice in which the melt-water content increases toward the ice. The cause of this band of dilute water is believed to be the scattering southward of ice from a diffuse ice margin accompanied by melting. This band varies in width in response to local phenomenon.

North of the ice edge the fresh-water content of the water column is found to be greater than that of more southerly water by an amount equivalent to the approximate thickness of the ice cover.

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